INSTRUCTOR: Charlie Leonard

GPS Concepts – Introduction to the Global Positioning

System

**COURSE:** Field Applications of GPS for Fire Management

Unit A, Lesson 1

# **Lesson Objectives**

LESSON:

1. Describe at least three sources of GPS signal error, and ways to mitigate or reduce those errors.

- 2. Identify and describe the three segments of the Global Positioning System.
- 3. Describe two technologies that enhance the accuracy of GPS positioning and collected position data.
- 4. Complete the Pre-Work Quiz.

Raleigh, North Carolina, April 8 – 12, 2002
Sacramento, California, April 22 – 26, 2002

Field Applications of GPS for Fire Management

Toto

NAVSTAR GPS

Unit A, Lesson 1

Charlie Leonard, 1999

NAVSTAR GPS: Navigation Satellite Timing and Ranging Global Positioning System.

# Unit A Lesson 1 Pre-Work

### **Lesson Objectives:**

- > Describe at least three sources of GPS signal error, and ways to mitigate or reduce those errors.
- > Identify the three segments of the Global Positioning System and describe the purpose of each.
- > Describe two technologies that enhance the accuracy of GPS positioning and collected position data.
- > Successfully complete the Pre-Work Quiz.

### **Unit A Lesson 1 Pre-Work**

#### **Lesson Objectives:**

Describe at least three sources of GPS signal error, and ways to mitigate or reduce those errors. Identify the three segments of the Global Positioning System and the purpose of each.

Describe two technologies that enhance the accuracy of GPS positioning and collected position data. Complete the Pre-Work Quiz.

# **Unit A Lesson 1 Pre-Work Outline**

- > A Brief history of the GPS
- > Segments of the system
- > How GPS works
- > Problems with the GPS
- > Advancements in the GPS
- > Projections, Datums and Coordinate Systems

#### **Lesson 1 Pre-Work Outline**

Lesson 1 will cover an introduction to the Global Positioning System, as well as a brief overview of how the Global Positioning System works. Problems associated with the GPS will also be covered, as well as advancements in GPS technology. The final segment of Lesson 1 will cover projections, datums and coordinate systems. Lesson 1 contains all of the information needed to complete the pre-work exercise. Referring to the glossary of GPS terms while reading the pre-work will help you better understand the material.

# The History of GPS

- > Feasibility studies begun in 1960's.
- > Pentagon appropriates funding in 1973.
- > First satellite launched in 1978.
- > System declared fully operational in April, 1995.

### The History of GPS

The Department of Defense issued a memorandum in 1973 naming the Air Force as the Executive Service for the initial development of a Defense Navigation Satellite System (DNSS). This system was eventually designated the **Navigation Satellite Timing and Ranging Global Positioning System** (NAVSTARGPS). The purpose of the GPS is to provide U.S. forces and its allies a means to navigate worldwide without the use of ground based navigation aids which are difficult to protect. The GPS also provides guidance for so-called "smart weapons."

Today the GPS is made up of a minimum of 24 primary satellites, and several in-orbit spares. The first satellite, a Phase 1, Block I satellite, was launched in 1978. The first 10 satellites were developmental satellites, part of the Block I system. Next, 23 production satellites, Block II design, were launched. The launch of the 24th satellite in 1994 completed the system as it is today. The number of in-orbit satellites varies due to ongoing replacement of aging satellites and the number of functioning spares in the constellation.

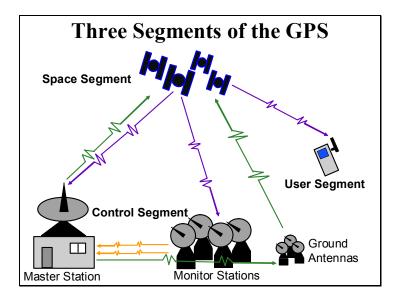
The U.S. Air Force Space Command formally declared the GPS satellite constellation as having met the requirement for Full Operational Capability on April 27, 1995. The system cost US taxpayers \$14 billion to develop and deploy, and costs millions more annually to maintain. Replacement satellites are constantly being built and launched into orbit.

In the late 1980's civilian scientists began to develop the GPS for non-military purposes. Since then GPS use has exploded in the private sector around the world. Many companies now provide products and services utilizing GPS. GPS today is a multi-billion dollar a year industry, and this has put enormous

pressure on the Pentagon to loosen its control of the system. In a surprise move the Pentagon set Selective Availability to zero in May, 2000. It did not do away with Selective Availability, but rather, merely set the time dithering to zero (no error). The Department of Defense retains the right to impose Selective Availability again without any prior notification if it deems necessary.

Over the past 10 years, GPS has evolved far beyond its military origins. The GPS is now an information resource supporting a wide range of civil, scientific, and commercial functions--from air traffic control to the Internet--with precise location and timing information. According to the Rand Corporation, the market for civilian applications now exceeds its military counterpart by roughly 8 to 1. The growth in civilian applications has spawned a booming market for GPS products and services. According to the GPS Industry Council, projected sales of commercial GPS equipment in the year 2000 were expected to total about \$8.5 billion. Presently both Japan and the European Community are exploring their own commercial systems. The United States would still have GPS for its own national security purposes, but might risk losing the economic benefits from past investments in the GPS if these other systems are developed.

How GPS Works				



# Three Segments of the Global Positioning System

The Control segment is made up of a Master Control Station (MCS), four monitor stations, and three ground antennas (plus one reserve antenna at Cape Canaveral used for pre-launch satellite testing) used to uplink data to satellites. Monitor Stations continuously receive GPS satellite transmissions (purple arrows), and relay this information in real time to the Master Control Station in Colorado (yellow arrows). The user segment also receives the same transmissions (purple arrow).

The MCS uplinks data to the GPS satellites (green arrows) on:

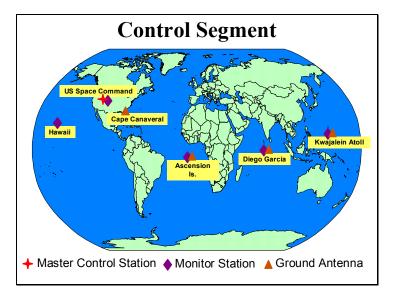
- -Clock-correction factors for each satellite; necessary to insure that all satellites are operating at the same precise time (known as "GPS Time").
- -Atmospheric data (reduces the amount of interference and distortion caused by signals passing through the ionosphere and troposphere).
- -Almanac. A log of all GPS satellite positions and health, which allows GPS receivers to identify which satellites are in its hemisphere, and at what times. Transmitted continuously from every satellite, the almanac allows GPS receivers to choose the best satellite signals for positioning. The almanac also contains signal information unique to each satellite (the pseudo random noise code), which is necessary for GPS receivers to do differentiate between satellite signals. The almanac is automatically downloaded from satellites whenever a receiver is collecting a GPS signal. An almanac can also be downloaded from a computer to a GPS receiver using a base station or other archived almanac.

-Ephemeris is transmitted by each satellite, and provides highly accurate satellite position (orbit) only for that individual GPS satellite. It does not include information about other satellites. This information is transmitted as a part of the time signal.

Space segment: more than 24 satellites (including in-orbit spares) in six orbital planes 20,200 kilometers (10,900 nautical miles) in space. Satellites downlink data to the Master Control Station and all GPS receivers, including:

- -Coded ranging signals (radio transmission time signals that allow receivers to triangulate their positions).
- -Ephemeris position information (a message transmitted every 30 seconds on the location of each satellite).
- -Atmospheric data (necessary to help reduce the amount of error introduced by the satellite signals passing through the atmosphere).
- -Almanac.

User Segment is made up of the military, industry and private users.



**Control Segment** 

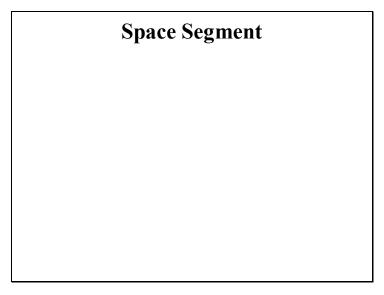
The primary mission of the **control segment** is to update the navigational message of the Global Positioning System. Information on the satellites is then transmitted to the Master Control Station where computations are made and an up-to-date navigation message is uploaded to the satellites; there may be several uploads per day, per satellite.

The Master Control Station (MCS, and also known as the Consolidated Satellite Operations Center). The Master Control Station is located at the US Air Force Space Command Center at Falcon AFB in Colorado Springs, CO. It's responsible for satellite control and overall system operations. Ephemeris (current satellite position and timing information transmitted as part of the satellite data message), almanac updates, atomic clock corrections, and Selective Availability data all originate from here. Uplinks to satellites occur primarily through ground antennas, but can also be uplinked at the MCS.

**Monitor stations (MS)** are located at Falcon Air Force Base, Hawaii, Kwajalein Atoll, Diego Garcia, and Ascension Island. These stations are unmanned, remote sensors that passively collect raw satellite signal data and re-transmit it in real time to the MCS for evaluation. Monitor stations basically function as very precise radio receivers, tracking each satellite in view at their locations (up to 11 satellites simultaneously on both L1 and L2 frequencies). They send their raw pseudo- range measurements and navigation message observations back to the MCS for processing in real time.

**Ground antennas** are remotely controlled by the MCS. They are located at Ascension, Diego Garcia, Kwajalein Atoll, and Cape Canaveral. Ground antennas transmit data commands received from the Master Control Station to GPS satellites within their sky view. They also collect telemetry data from the satellites. A secondary ground antenna is located at Cape Canaveral. Its primary function is pre-launch

testing of satellite systems. It can also transmit data to satellites in orbit when needed. Ground antennas are separate from monitor stations, though they are co-located.



### **Space Segment**

The **space segment** is an earth-orbiting constellation of more than 24 satellites (plus several in-orbit operational spares) in six orbital planes. The satellites are oriented at an angle of 55 degrees to the equator. The nominal circular orbit is 20,200-kilometer (10,900 nautical mile) altitude. Each satellite completes one earth orbit every twelve hours (two orbits every 24 hours). That's an orbital speed of about 1.8 miles per second. Each satellite travels from horizon to horizon in about 2 hours.

Each satellite has a life span of approximately 10 years, weighs approximately 2,000 pounds, and is about 17 feet across with the solar panels extended. Radio transmitter power is only 50 watts, or less. And each satellite is equipped with four atomic clocks: 2 cesium, and 2 rubidium, plus 3 nickel-cadmium batteries for backup power when a satellite is in earth eclipse.

Each satellite provides as part of its signal to GPS receivers:

#### -Clock correction:

Defines the precise time of satellite signal transmission.

#### -Almanac:

Constellation information (including location and health of satellites. Almanac data allows a receiver to acquire satellites as soon as it is turned on after an almanac has been downloaded into the receiver's memory. It takes approximately 12 - 13 minutes for a receiver to download a full almanac. GPS receivers download almanac data on a continuing basis.

#### -Ephemeris:

Current satellite position in space as a function of time.

Slide 9

# **User Segment**

- > Military.
- > Search and rescue.
- > Disaster relief.
- > Surveying.
- > Marine, aeronautical and terrestrial navigation.
- > Remote controlled vehicle and robot guidance.
- > Satellite positioning and tracking.
- > Shipping.
- > Geographic Information Systems (GIS).
- > Recreation.

**User Segment** 

# **Four Basic Functions of GPS**

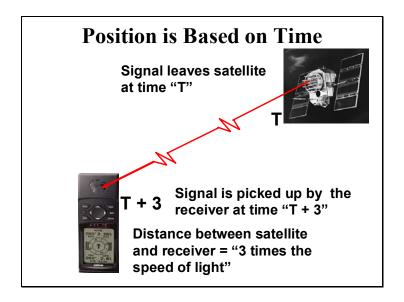
- > Position and coordinates.
- > The distance and direction between any two waypoints, or a position and a waypoint.
- > Travel progress reports.
- > Accurate time measurement.

#### The Four Basic Functions of the GPS

The GPS uses the principle of trilateration. That is, the user's receiver determines the distance from itself to each of the satellites it is acquiring. Since the positions of the satellites are known through part of the constellation's broadcast information, the user's position can be calculated.

#### The basic functions of GPS fall into four categories:

- **1) Position and waypoint coordinates.** GPS, through the receiver, provides position or waypoint information for its current location or for any remote location on the earth, and display that information in a variety of coordinates.
- 2) The distance and direction between the receiver's position and a stored waypoint, or between two remote waypoints.
- **3) Velocity reports:** Distance to and between waypoints; tracking to a waypoint; heading (direction of travel); speed; and estimated time of arrival, estimated time enroute, and velocity made good.
- **4) Accurate time measurement:** GPS has become the universal timepiece, allowing any two receivers (as well as any two clocks or watches) to be synchronized to within milliseconds of each other anywhere in the world.



#### Position is Based on Time

The Global Positioning System triangulates (called "trilateration") a GPS receiver's position by using a simple formula:

#### **Velocity x Time = Distance**

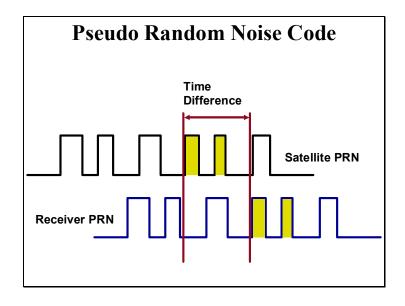
GPS satellites continuously transmit digital radio pulses at specific, known times. And by measuring the exact instant when the pulses arrive, the receiving equipment can determine the distance to each satellite. But in order for this to work, the receiver's internal clock must be synchronized with the system's atomic clocks. The synchronization must be precise for a GPS receiver to determine an accurate position. An error of as little as a millionth of a second can translate to a position error of about 300 meters on the ground.

In order to do this the GPS receiver calculates what are called pseudo-ranges ("false" ranges), which are approximate calculated distances to every satellite the receiver has acquired. Ideally at least four satellites are needed to provide a precise position.

For example, if a GPS radio signal leaves the satellite at precisely T+ 0 nanoseconds (billionths of a second), travels at 186,000 miles per second to the earth, and arrives at the receiver at precisely T+ 645,160 nanoseconds later, then it traveled 12,000 miles (12,000 miles @ 186,000 miles per second = 64.516 milliseconds, or 645,160 nanoseconds). Unfortunately, the receiver at first doesn't know the precise distance from itself to the satellite, so it makes an educated guess (largely based on almanac and ephemeris data it has collected from the satellites) – a pseudo-range. The receiver does this for every satellite signal it acquires. Each satellite has its own unique pseudo random noise (PRN) code, allowing

the receiver to keep the signals separated. In other words, it's an ID code unique to each satellite. We refer to satellites by their PRN number, currently numbered from 1 through 39 (these numbers will appear on the GPS receiver status screen for each satellite being acquired).

If GPS satellites communicated to GPS receivers in English, the conversation might sound something like this: "I'm satellite X, my position is currently Y, and this message was sent at time T."



How A Receiver Determines Its Position

Each satellite transmits a specific code (**ephemeris data**), a **coarse acquisition (C/A)** code (which contains information on that satellite's position), GPS system time, and a message on the health and accuracy of the transmitted data (**almanac**). The GPS uses two frequencies to accomplish data transmission, L1 and L2 (more about these later). Another frequency (L3) is planned for the next generation of satellites to enhance position and navigation precision of GPS receivers.

**Ephemeris (orbital) data** is constantly transmitted by each satellite and contains an accurate description of the satellite position <u>as a function of time</u>. Satellite orbit pertains to altitude, position and speed of the satellite. Distance to a satellite is determined by measuring how long a radio signal sent by that satellite takes to reach a GPS receiver.

The **pseudo random noise (PRN)** code is a fundamental part of the GPS. It's just a very complicated digital code; a complex sequence of "on" and "off" pulses (see the diagram). The signal is so complicated that it almost looks like random electrical noise (similar to the "snow" you might see on your TV). Hence the name "pseudo-random noise."

When a GPS receiver acquires a GPS signal it examines the satellite's incoming **PRN** and begins generating an identical digital signal to mimic the satellite signal. The receiver matches each satellite's C/A code with an identical copy of the code contained in the receiver's database (obtained from the downloaded **almanac**). Its next task is to try and determine how long ago the PRN was generated. But there's a problem. As explained earlier, each satellite is equipped with four atomic clocks; clocks which are constantly monitored and updated by the Master Control Station. The GPS receiver on the other hand

is equipped only with a single digital clock comparable to a cheap wrist watch. As described earlier, the only way for the receiver to triangulate an accurate position is if it can accurately measure the precise travel time of the satellite radio signal. A discrepancy of just a few nanoseconds between GPS Time and the GPS receiver will cause an error of hundreds of meters on the ground.

So the GPS receiver uses a clever technique to calculate the precise time it took for the GPS signal to reach it. By shifting its copy of the satellite's PRN code in a matching process, and by comparing this shift with its own internal clock, the receiver can calculate how long it took the signal to travel from the satellite to the receiver. By comparing the time difference between the two, and multiplying that time by the 186,000 miles per second travel speed of the signal, the receiver can *roughly* determine the distance separating it from the satellite. This process is repeated with every satellite signal the receiver locks on to. The distance between satellite and receiver derived from this method of computing distance is called a **pseudo-range** because it's not a direct measurement of distance, but rather a measurement based on time. Pseudo-range is subject to several error sources, such as delays caused by the atmosphere, and multipath interference.

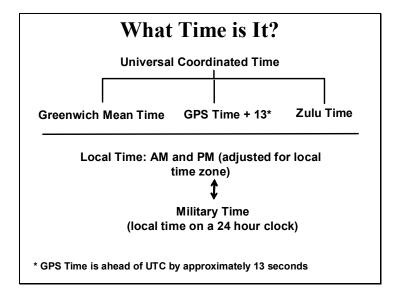
Here's a simplified example of how a GPS receiver synchronizes itself with GPS Time for precise positioning. Imagine that the GPS satellite signal is a song being broadcast from a radio station. The GPS receiver is a record player which is playing the same song, but it's not synchronized to the broadcast song. By speeding up or slowing down the turntable, the two songs can be precisely matched. They become synchronized. Similarly, the GPS receiver synchronizes its digital signal to match that of the satellite's.

Once the receiver has its internally generated code in synch with the satellite's code it can determine a pseudo-range distance to the satellite. But when the receiver is picking up only one, two, or three satellites, a very precise position still cannot be accurately determined. This is because the receiver's internal clock is not nearly as accurate as, nor precisely in synch with, **GPS Time**. So the first signal comparisons are rough approximations. With three satellite signal locks a receiver can only calculate a 2D (two dimensional) position fix. A fourth satellite signal is required to provide the final refinement of the receiver's internal clock to match GPS Time, and produce a good 3D (three dimensional) position. The clocks on each satellite are accurate to about one nanosecond per year. But the digital clocks on GPS receivers are only accurate to a minute or two each year. If the receiver is having trouble achieving good satellite signals, or holding on to those signals, it may need more than four satellites to be able to synchronize its clock with the satellite clocks. Once a receiver achieves four or more good signal locks, it uses its own internal trilateration algorithm to determine its position.

**Almanac data** includes constellation information (including location and health of satellites) that is transmitted by the satellites and collected by the receiver. Almanac data allows your receiver to quickly acquire satellites as soon as it is turned on. Satellite constellation updates, atomic clock corrections, and Selective Availability data all originate from here.

Since **GPS** Time is one of the most important components of the GPS, it's important to understand what it is. GPS Time is measured in weeks and seconds from 24:00:00, January 5, 1980 and is steered (adjusted) to within one microsecond of **Universal Coordinated Time** (**UTC**). But because GPS Time has no leap seconds ("official" earth time is periodically adjusted to compensate for the gradual slowing of the of the earth's rotation) it is actually ahead of UTC by several seconds. Universal Coordinated Time is computed from GPS Time using the UTC correction parameters sent by the Master Control Station to the satellite constellation as part of the navigation data bits. At the transition between 23:59:59 UTC on June 30, 1997 and 00:00:00 UTC on July 1, 1997, UTC time was retarded an additional one second, putting GPS Time ahead of UTC time by thirteen seconds.

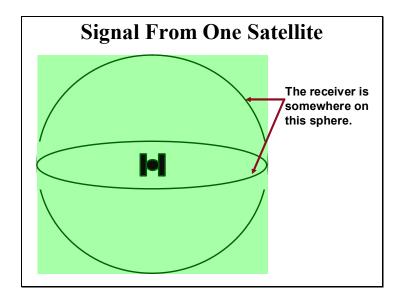
Once a GPS receiver has achieved a solid 3D position, its clock display will be updated to reflect GPS Time, which will be accurate to within 350 nanoseconds UTC for civilian receivers as specified by the U.S. Space Command (one nanosecond equals a billionth of a second, so 350 ns is about 1/3 of a millisecond). Adjusted for time zones, every clock set to GPS Time around the world will show the same precise time. It's important to note that setting an incorrect time zone(+ or – from UTC) in a GPS receiver has no effect on the receiver's ability to provide an accurate position. An incorrect time zone merely provides different time, not inaccurate time.



#### What Time is It?

Universal Time Coordinated (UTC) is the same as Greenwich Mean Time (GMT) (centered in Greenwich, England, hence the name), which is also known as Zulu Time (a term used mostly by pilots and the military). The world is broken down into 24 time zones of one hour each (with a few localized half hour zones sprinkled here and there). Universal Time Coordinated is the "official" time standard recognized by most of the world, and it forms the basis for GMT and Zulu time. Midnight in Greenwich, England is 0000 hours UTC and Zulu. Each time zone east of Greenwich adds one hour, and each time zone west subtracts an hour. Most of the United States practices Daylight Saving Time during the summer, which adds one hour to each time zone. The rest of the year is called Standard Time. When it's midnight in Greenwich, it's five hours (or five time zones) behind in New York during Standard Time (7:00 PM), or four hours behind during Daylight Saving Time (8:00 PM).

Universal Time Coordinated is not military time. Military time is simply using a 24 hour clock to represent local time. For example, 1800 hours in military time is 6:00 p.m. local time. But 1800 hours Zulu (or UTC, or Greenwich Time) is 6:00 p.m. in Greenwich, England. Or, 1800 hours military time in Boise, Idaho is 2400 hours in UTC during Daylight Saving Time, or 0100 hours during Mountain Standard Time (Boise lies in the seventh time zone behind GMT). But if it's 9:00 AM (0900 military time) in Boise, and you tell someone that you will meet them at a pub at 1600 Zulu (assuming it's Standard Time), then you had better hurry because 0900 Mountain Standard Time *is* 1600 Zulu Time!



#### How a Receiver Determines Its Position

Traveling at the speed of light each satellite radio signal takes a brief, but measurable amount of time to reach a GPS receiver. The difference between when the signal is sent and the time it is received, multiplied by the speed of light, enables a GPS receiver to accurately calculate the distance between it and each satellite, provided that several factors are met.

Those factors are:

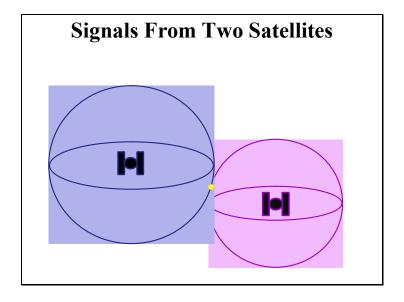
Good satellite signal lock by the GPS receiver (already covered)

A minimum of four satellite signals (discussed next)

Good satellite geometry (discussed in later)

When a GPS receiver is turned on it immediately begins searching the sky for satellite signals. Eventually it locates and acquires its first signal. Reading this signal the receiver collects **ephemeris data**. This provides updated information on current satellite positions. The receiver uses this information in conjunction with a current almanac it acquired on a previous outing, and stored in its memory. If the receiver does not have a current almanac (such as a new, unused, receiver), or was moved more than 300 miles while turned off, it must collect a new almanac, which will take about 12-13 minutes after the first satellite signal is acquired. Why the need for a new almanac if the receiver is moved more than 300 miles while turned off? Beyond 300 miles from its last used location the receiver is presumed to be using different GPS satellites, and therefore should download a new almanac to reflect the new PRN codes. (If the receiver is turned on while moving over 300 miles, it continuously updates its almanac automatically.)

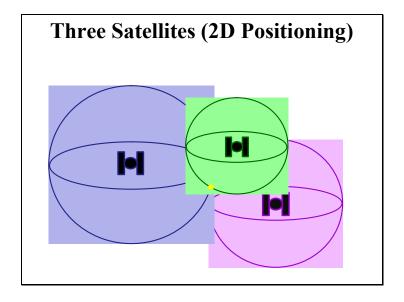
In the graphic, the GPS receiver calculates a rough location somewhere on this three dimensional sphere, which is actually thousands of miles in diameter. All the receiver can do at this point is collect system data and search for more satellites.



How a Receiver Determines Its Position (cont.)

In a perfect world, where both satellite and receiver clocks were perfectly synchronized with each other, an accurate position could be determined from just two satellites. However, most receivers are incapable of calculating an accurate position using just two satellites. The yellow dot in the example represents the approximate location of where the receiver thinks it is based on the information provided by two satellites. At least now the receiver knows that it is somewhere at the intersection of those two satellite signals. But that's the only improvement in its position calculations.

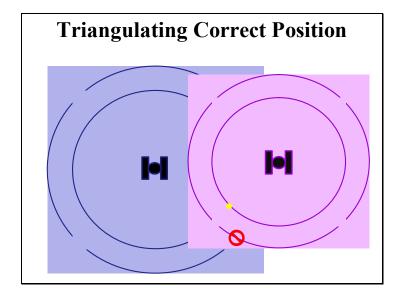
The satellite signal spheres should intersect at precisely the receiver's location, but don't because the clock in the GPS receiver isn't synchronized with GPS Time. So the receiver estimates a "pseudo-range" to each satellite.



### How a Receiver Determines Its Position (cont.)

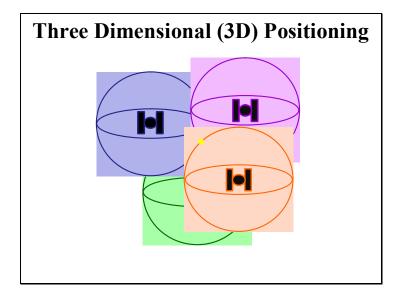
Three satellites can provide only a two-dimensional (2D) position. Without manually entering the receiver's exact elevation (most GPS receivers don't allow elevation to be entered manually), a 2D position may be off by several kilometers on the ground. If the exact elevation of the GPS receiver is known, entering that elevation into a receiver with this capability replaces the need for a fourth satellite signal to allow a receiver to triangulate a precise position. It essentially uses elevation in lieu of a fourth satellite, and makes the appropriate adjustments to triangulate a reasonably good 3D position. But without manual elevation correction most GPS receivers must rely on a fourth satellite to provide the final clock correction necessary to calculate a 3D position. Until a fourth satellite signal is acquired the receiver will not be able to determine x and y horizontal, and z vertical positioning (a true 3D position). This is because the fourth satellite signal is used by the receiver not to provide more position data, but, rather, the final time correction factor in its ranging calculations.

As a rule, 2D positions should always be avoided whenever possible. Use 2D positioning only when a 3D position is not possible, but be aware of the horizontal error inherent in any 2D position. The inability of a GPS receiver to triangulate a 3D position may be due to a variety of factors, including user error, poor satellite geometry, and harsh landscape conditions (tall buildings, canyons, and dense tree cover among others). As will be shown later in the course, all GPS receivers provide some means for informing the user which mode they are operating in. It's up to the user to be aware of the errors associated with 2D positioning.



How a Receiver Determines Its Position (cont.)

Unfortunately, accessing only two or three satellite signals the clock in the GPS receiver cannot yet be synchronized precisely with GPS Time. The pseudo-range spheres (the diagram here shows only two satellites for simplification), as interpreted by the GPS receiver, will either be just a little too large (if the receiver's clock is running faster than GPS Time) or too small (if the receiver's clock is slower than GPS Time). The spheres will not intersect with each other. In this example, the red dot could be the false pseudo-range position if the GPS receiver's clock is running faster than GPS Time, or the yellow dot is the position if the receiver's clock is slower than GPS Time.



# How a receiver determines its position (cont.)

For a GPS receiver to achieve **three-dimensional (3D)** positioning it needs to acquire four or more satellite signals. A 3D position is comprised of X and Y (horizontal), Z (vertical) position, and precise time (not varying more than a few hundred nanoseconds). The receiver's processor uses the fourth satellite pseudo-range as a timing cross check to estimate the discrepancy in its own ranging measurements and calculate the amount of time offset needed to bring its own clock in line with GPS Time (recall the radio station and record player simultaneously playing the same song). Since any offset from GPS Time will affect all its measurements, the receiver uses a few simple algebraic calculations to come up with a single correction factor that it can add or subtract from all its timing measurements that will cause all the satellite spheres to intersect at a single point (x, y, and z). That correction synchronizes the receiver's clock with GPS Time. Now the receiver essentially has atomic clock accuracy with the time correction factor needed to achieve precise 3D positioning. The pseudo-ranges calculated by the GPS receiver will correspond to the four pseudo-range spheres surrounding the satellites, causing the four spheres to intersect at precisely the receiver's location (the dot in the diagram).

# Selective Availability (S/A)

- > The Defense Department dithered the satellite time message, reducing position accuracy to some GPS users.
- > S/A was designed to prevent America's enemies from using GPS against us and our allies.
- > In May 2000 the Pentagon reduced S/A to zero meters error.
- > S/A could be reactivated at any time by the Pentagon.

# Selective Availability (Anti-Spoofing)

Selective Availability (S/A) was the intentional degradation of the Standard Positioning Service (SPS) signals by a time varying bias. Selective Availability is controlled by the DOD to limit accuracy for non-U. S. military and government users. The potential accuracy of the coarse acquisition (C/A) code at around 30 meters was reduced by Selective Availability up to 100 meters. In May, 2000, bowing to pressure from business and the White House, the Pentagon set Selective Availability to zero. The Pentagon did not turn S/A off, but rather merely reduced the amount of signal dithering to zero meters, effectively eliminating intentional position errors.

During the recent Afghanistan conflict there has been no sign that U.S. Space Command has reactivated Selective Availability, and it does not appear likely that this will happen. However, the Pentagon continues to retain the ability to reactivate S/A without notice to non government GPS users. So it's important to understand what Selective Availability is, and to be aware that it could be reactivated by the U.S. military at any time without prior notification.

\_\_\_\_\_

Slide 20

### **Sources of GPS Error**

Standard Positioning Service (SPS ): Civilian Users

Source Amount of Error
> Satellite clocks: 1.5 to 3.6 meters

> Orbital errors: < 1 meter

> Ionosphere:
> Troposphere:
> Receiver noise:
> Multipath:
5.0 to 7.0 meters
0.5 to 0.7 meters
0.3 to 1.5 meters
0.6 to 1.2 meters

> Selective Availability (see notes)

> User error: Up to a kilometer or more

Errors are cumulative and increased by PDOP.

#### Sources of GPS Error

**Satellite clock errors:** Caused by slight discrepancies in each satellite's four atomic clocks (two cesium and two rubidium). Errors are monitored and corrected by the Master Control Station.

**Orbit errors:** Satellite orbit (referred to as "satellite ephemeris") pertains to the altitude, position and speed of the satellite. Satellite orbits vary due to gravitational pull and solar pressure fluctuations. Orbit errors are also monitored and corrected by the Master Control Station.

**lonospheric interference**: The ionosphere is the layer of the atmosphere from 50 to 500 km that consists primarily of ionized air. Ionospheric interference causes the GPS satellite radio signals to be refracted as they pass through the earth's atmosphere – causing the signals to slow down. This results in inaccurate triangulation measurements by GPS receivers on the ground. Even though the satellite signals contain correction information for ionospheric interference, it can only remove about half of the possible 70 nanoseconds of delay leaving up to a ten meter error on the ground. GPS receivers also attempt to "average" the amount of signal speed reduction caused by the atmosphere when they calculate a position fix. But this works only to a point. Fortunately, error caused by atmospheric conditions is usually less than 10 meters. This source of error has been further reduced with the aid of the Wide Area Augmentation System (WAAS).

**Tropospheric interference**: The troposphere is the lower layer of the earth's atmosphere (below 13 km) that experiences the changes in temperature, pressure, and humidity associated with weather changes. Tropospheric interference is fairly insignificant to GPS.

Receiver noise is simply the electromagnetic field that the receiver's internal electronics generate when it's turned on. Electromagnetic fields tend to distort radio waves. This affects the time the travel time of

the GPS signals before they can be processed by the receiver. Remote antennas can help to alleviate this noise. This error cannot be corrected by the GPS receiver.

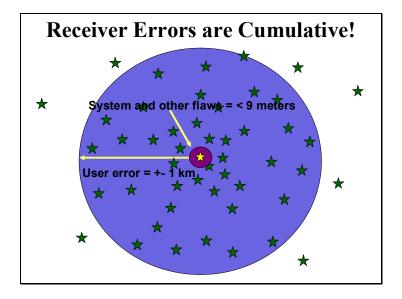
**Multipath interference** is caused by reflected radio signals from surfaces near the GPS receiver that can either interfere with or be mistaken for the true signal that follows an uninterrupted path from a satellite. An example of multipath is the ghosting image that appears on a TV equipped with rabbit ear antennas. Multipath is difficult to detect and sometimes impossible for the user to avoid, or for the receiver to correct.

**Selective Availability** was the Defense Department's intentional skewing (referred to as "dithering") of the satellite time message sent to the receiver. By dithering the time message just a few nanoseconds, the receiver was unable to triangulate its position with pinpoint accuracy. This was a defensive feature built into the system to prevent America's adversaries from using GPS against us. Selective Availability was reduced by the Department of Defense in May of 2000, and is currently not considered a source of error.

**Control Segment blunders** due to computer glitches or human error can cause position errors from several meters to hundreds of kilometers. Checks and balances by the Air Force Space Command virtually eliminates any blunders in the Control and Space segments of the GPS.

**User mistakes** account for most GPS errors. Incorrect datum and typographic errors when inputting coordinates into a GPS receiver can result in errors up to many kilometers. Unknowingly relying a 2D position instead of a 3D position can also result in substantial errors on the ground. A GPS receiver has no way identifying and correcting user mistakes.

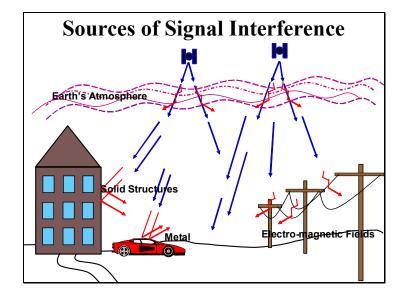
**Errors in GPS are cumulative**, and are compounded by position dilution of precision (PDOP). It is the user's responsibility to insure the accuracy of the data being collected with the GPS.



#### **Receiver Errors are Cumulative!**

As shown in the previous diagram, the Global Positioning System can contribute system errors of up to about nine meters on the ground. However, user errors can dramatically increase that to a kilometer or more. Among the most common user errors include using a 2D position instead of a 3D position, mismatched datums between a GPS receiver and a user's map, and high position dilution of precision (PDOP). In the case of two dimensional positioning, the error occurs because the GPS receiver isn't acquiring enough satellite signals (usually four or more) to provide a precise position. The difference can be as much as several kilometers from a user's true location. Position dilution of precision (PDOP) will be covered later in this lesson. The importance of not using mismatched datums will be covered in the mapping section of the course.

In the above example, the green stars represent the potential positions a GPS receiver can triangulate for a user depending on the amount error incorporated into that receiver's triangulation calculations. The blue circle is a gross example of poor user control over the GPS receiver, and the purple circle is the uncontrollable circle of error possible through system errors. The yellow star represents the hypothetical true location of the user.



# **Sources of Signal Interference**

**Atmospheric conditions**, specifically in the ionosphere (the layer of earth's atmosphere that causes the northern lights), can cause radio signals traveling at 186,000 miles per second to slow down slightly as they pass through to the earth's surface. As a rule, GPS receivers are programmed to "average" the amount of slowing when they calculate a position fix. But this works only to a point. Fortunately, error caused by atmospheric conditions is generally less than 10 meters.

The Wide Area Augmentation System also reduces the amount of lonospheric distortion. Only GPS receivers capable of receiving the WAAS signal will benefit from this. (More about WAAS later.)

Multipath interference is nothing more than satellite signals reflecting off objects, or being occluded entirely by an object. It's similar to the ghost images that appear in TV signals passing through rabbit ears. When the signal bounces off an object it no longer follows a straight path to the receiver, and the time it takes for the signal to reach the GPS receiver's antenna is altered in a way that cannot be measured. The GPS receiver cannot accurately calculate the true time of signal arrival, resulting in inaccurate position measurements. In order for a GPS receiver to accurately triangulate its position, it must have a clean and unaltered signal from the satellite, one that has not been diverted to another location on its way to the receiver.

When using GPS in a vehicle, placing the receiver antenna on the roof of the vehicle will eliminate most signal interference caused by the metal vehicle. Using a GPS receiver placed on the dashboard will always have some multipath interference.

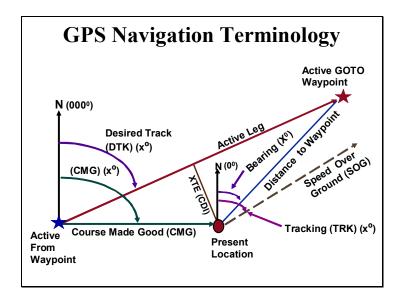
**Electro-magnetic fields (EMF)** also distort radio signals. A GPS receiver under or near power lines or other sources of electrical generation or transmission will distort the GPS radio signal, thus altering its direct path to the receiver.

Even the **human body** can cause signal interference. Holding a GPS receiver close to the body can block some satellite signals and hinder accurate positioning. If a GPS receiver must be hand held without benefit of an external antenna, facing to the south can help to alleviate some of this error because the majority of GPS satellites are oriented more in the earth's southern hemisphere.

**Using GPS Receivers for Positioning and Navigation** 

**Using GPS Receivers for Positioning and Navigation** 

\_\_\_\_\_



### **GPS Navigation Terminology**

The following are common terms used for navigating with GPS.

- Active from waypoint is your starting waypoint, or the receiver's last waypoint in an active route.
- **Active GOTO waypoint** is your designated destination in the receiver, whether in an active route, or as a single waypoint.
- **Active leg** is always a straight line between the last waypoint and the GOTO waypoint. A GPS receiver always plots the most efficient, straight-line course of travel between two points the active leg. If the receiver is following a route, the active leg will be the desired track between the last waypoint in the route, and the next waypoint in the route. If the receiver has deviated from the route, the receiver selects the closest leg to its position and makes it the active leg in the route (the next waypoint in the route list becomes the GOTO destination waypoint). The distance and bearing between two waypoints stored in a GPS receiver's memory can be determined even if the receiver is at another location.

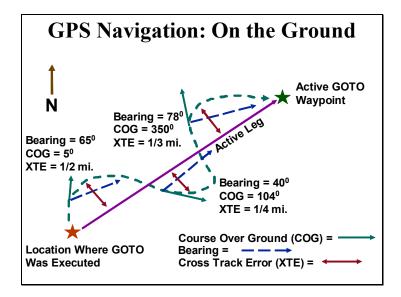
If you are using **GOTO** to navigate to a waypoint, but not from a previous waypoint, then there is no actual active leg. The receiver will provide a continuous bearing from your present moving position to the GOTO waypoint, and no XTE will be expressed.

- **Bearing**: In GPS the term bearing is used in place of **azimuth**. As used in GPS, bearing is the compass direction (expressed in degrees) from your present position to your desired destination waypoint, or the compass direction between any two waypoints. It's not the actual direction you are heading - unless you're heading also matches the bearing to your destination.

- Course Made Good (CMG) or Course Over Ground (COG) is your present direction of travel expressed in degrees from north. It is not necessarily the most direct path to a GOTO waypoint. If traveling from one waypoint to another (using GOTO), then XTE (see below) will show the distance of

deviation of your actual route from the active leg (a straight line) between those waypoints.

- **Crosstrack Error (XTE)** is the distance off the desired track (active leg) on either side of the active leg. It's the linear difference between the Desired Track (DTK) and your actual Course Made Good (CMG). Some GPS receivers use a **Course Deviation Indicator (CDI)** to graphically show the amount and direction of XTE.
- **Desired track (DTK)** is shown in degrees from north. It's a function of GOTO. DTK is measured along the active leg (a straight line between two waypoints in a route), or from your current position to a designated GOTO waypoint (when not navigating a route).
- **Distance to waypoint** is from the receiver to the GOTO waypoint.
- **North** is expressed in degrees (000 ☐ (whether the receiver is set for true north, magnetic north, grid north, or user defined north).
- Speed Over Ground is the velocity you are traveling.
- **Tracking** is the direction you are moving, expressed in degrees from north. In GPS it's the same as **heading** (the direction you are actually traveling).



**GPS Navigation: On the Ground** 

The star in the lower left corner represents the starting point of a route or track. The star in the upper right is the destination programmed as a waypoint into the GPS receiver. The straight line between the two stars is the bearing to the destination. Unfortunately, the user is unable to follow the straight course plotted by the receiver, and he or she meanders over the ground (the dashed undulating line). Despite this the receiver is able to continuously the navigation information it gives to the user (represented by the arrows). Unlike a compass, which would require sighting a new bearing every time there was a course change, the GPS receiver updates the navigation message automatically in real time.

**Course Over Ground (COG)** or **Course Made Good (CMG)** is the bearing from the active from position to your present position expressed in degrees from north. It can also be the bearing from your starting point to your present position. In other words, it's the actual route you have followed so far - not necessarily the most direct route (that's where XTE comes in).

**Bearing**: When a designated waypoint is entered into a GPS receiver, and the GOTO function activated, the receiver plots a straight line course (bearing) to that destination from its current location. But due to obstacles on the ground it's almost impossible to follow a straight line course. The user is forced to meander over the landscape while enroute to user's destination. The GPS receiver however never loses sight of its target, and always maintains an accurate bearing to the GOTO waypoint regardless of the user's direction of travel (heading).

As the user negotiates around obstacles, his or her course over ground (COG) continually changes. If the user is heading 5°, the GPS bearing to target may be 65°. But if the user changes course and heads 104°, bearing will correspondingly change to 40°.

The "active leg" does not change during the user's travels until he or she travels beyond the GOTO waypoint. If the user is traveling a predetermined route, the GPS receiver will automatically select the next route leg in the sequence closest to the current location of the receiver (making it the "active" leg). If there is not a route activated, the receiver will continue to provide navigation information to the GOTO destination waypoint.

Cross track error (XTE) lets the navigator know how far he or she has deviated from the "active leg." Remember that the active leg is always a straight line from the position where GOTO was activated to the destination waypoint. XTE has no real value in land navigation beyond keeping track of how far the user has deviated from his or her original course. Cross track error is often presented in a GPS receiver in the form of a course deviation indicator (CDI). A CDI is usually a bar graph with a "floating" point indicating the amount of current deviation from the active leg either left or right of the active leg.

## **Position Fix**

- > A position is based on real-time satellite tracking.
- > It's defined by a set of coordinates.
- > It has no name.
- > A position represents only an *approximation* of the receiver's true location.
- > A position is not static. It changes constantly as the GPS receiver moves (or wanders due to random errors).
- > A receiver must be in 2D or 3D mode (at least 3 or 4 satellites acquired) in order to provide a position fix.
- > 3D mode dramatically improves position accuracy.

## Position fix vs. Stored Waypoint

In the GPS position fixes and waypoints are two distinctly different things.

#### A position fix:

Is based on real-time satellite tracking (usually the receiver must be receiving 3 or more satellite signals). Represents only an *approximation* of the receiver's true position (due to inherent errors, as described earlier).

Has no name or other reference information.

Is not static, and constantly changes as the receiver moves, or even while the receiver remains stationary.

## Waypoint

- > A waypoint is based on coordinates entered into a GPS receiver's memory.
- It can be either a saved position fix, or user entered coordinates.
- > It can be created for any remote point on earth.
- > It must have a receiver designated code or number, or a user supplied name.
- > Once entered and saved, a waypoint remains unchanged in the receiver's memory until edited or deleted.

#### **Waypoint**

#### A waypoint:

Is based on geographic coordinate values entered into the receiver's memory.

Represents either a saved receiver position fix, or user entered coordinates.

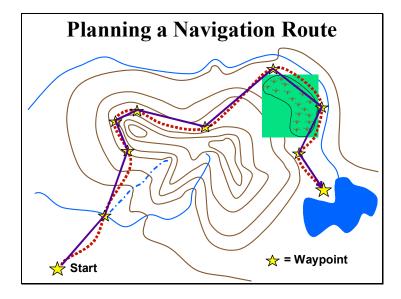
Will have designated alphanumeric name, or a user supplied name.

Once entered and saved it remains static in the GPS receiver's memory until edited or deleted.

Can represent any remote location on earth.

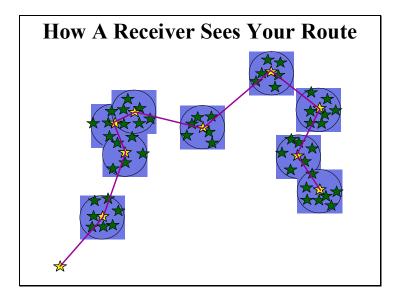
To turn a position fix into a waypoint is simply a matter of saving the receiver's current position fix. The receiver must be locked on to enough satellites to provide at least a two-dimensional (2D), or three-dimensional (3D) fix. The receiver will give the position coordinates an alpha-numeric name, or the user can designate a unique name. Once this happens the position fix becomes a waypoint with static coordinates saved in memory.

A waypoint can also be created from coordinates derived other than by GPS. Coordinates on a map can become a waypoint. Coordinates radioed from person in a remote location to another person can also become a waypoint once they are programmed into a GPS receiver.



## **Planning a Navigation Route**

A hiker plans to hike three miles to a lake from a parking lot. Using a map the hiker plots the coordinates of waypoints along the intended route (the stars in the diagram) and programs them into a GPS receiver. The receiver interprets the legs between the waypoints as straight lines. The hiker on the other hand must negotiate around obstacles during the hike, and walks a route depicted by the dotted line. While the trail to the lake may be three miles in length, the GPS receiver may calculate the distance as much shorter because it can't account for the hiker's meandering path. The next diagram demonstrates how the GPS receiver might see the "route" the hiker has programmed into its memory.



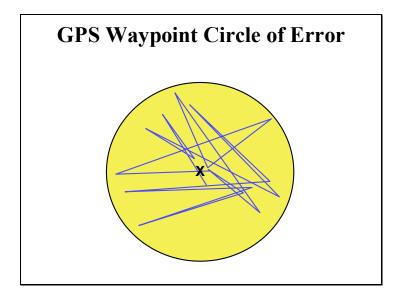
How a GPS Receiver "Sees" the Route

If you could visualize how a GPS receiver "sees" a route programmed into its memory, it might look something like the above diagram.

Each plotted waypoint is represented by a yellow star. However due to signal interference and other errors the receiver is fooled into seeing multiple <u>potential</u> waypoints at each site within the limits of the current sphere of error (which could be anywhere from a couple of meters to more than a kilometer depending on the cumulative effects of errors the receiver is subjected to).

As the receiver approaches each designated waypoint, errors identify multiple potential sites where the receiver thinks the waypoint coordinates may exist. As the navigator moves closer to, and around, the target waypoint, the receiver is continuously fooled by conflicting GPS signals and/or other errors. When approaching a waypoint or destination it's up to the user to not rely on the receiver to navigate the last few meters, but rather to use other means of navigation to reach the destination.

Here's an example. Let's say that a mountain climber is navigating by GPS back to his tent in a whiteout. Visibility is only twenty feet. The climber had programmed the tent's location into his GPS receiver that morning before leaving camp. As the climber nears his tent, say roughly fifty feet, the GPS receiver may no longer be reliable for navigating the last short distance to the tent. The next diagram demonstrates the conflicting path a GPS receiver may plot as it nears a waypoint.



**GPS Waypoint Circle of Error** 

As a GPS receiver approaches its GOTO destination waypoint, it usually will not be able to go directly to the precise coordinates of the waypoint (here defined by the red X). What a GPS receiver tends to do is bounce the receiver around the destination point (as shown by the jagged line). Usually this doesn't occur until the receiver is within ten meters or less of the waypoint (though the distance can vary due to other errors), and the diameter of circle of error is generally fairly small.

When a GPS navigator gets this close to a destination waypoint, he or she needs to rely on other means to facilitate navigating the final few meters to the destination waypoint. Usually this means using geographic features on the ground, a map, or "dead reckoning." The yellow circle is representative of the area of potential receiver "confusion."

**GPS Dilution of Precision and Its Affects On GPS Accuracy** 

# **GPS Satellite Geometry**

- Satellite geometry can affect the quality of GPS signals and accuracy of receiver trilateration.
- > Dilution of Precision (DOP) reflects each satellite's position relative to the other satellites being accessed by a receiver.
- > There are five distinct kinds of DOP.
- Position Dilution of Precision (PDOP) is the DOP value used most commonly in GPS to determine the quality of a receiver's position.
- > It's usually up to the GPS receiver to pick satellites which provide the best position triangulation.
- > Some GPS receivers allow DOP to be manipulated by the user.

#### **GPS Satellite Geometry (PDOP)**

Satellite position geometry can affect the quality of GPS signals and accuracy of receiver trilateration.

Dilution of Precision (DOP) reflects each satellite's position relative to the other satellites being accessed by a receiver.

There are five different kinds of DOP:

GDOP: Geometric Dilution of Precision (refers to GPS satellite orbit anomalies)

VDOP: Vertical Dilution of Precision (imperfect height measurements on the ground)

HDOP: Horizontal Dilution of Precision (imperfect horizontal measurements on the ground)

TDOP: Time Dilution of Precision (refers to slight anomalies in time measurements)

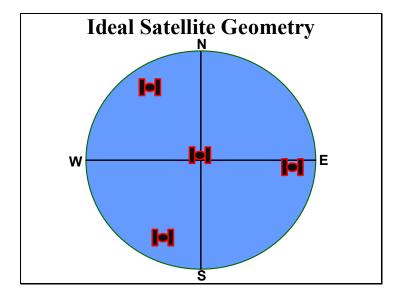
PDOP: Position Dilution of Precision (three-dimensional position errors)

Position Dilution of Precision (PDOP) is the DOP value used most commonly in GPS to determine the overall quality of a receiver's position.

DOP can be used as an indicator of the quality of a receiver's triangulated position.

It's usually up to the GPS receiver to pick satellites which provide the best position triangulation.

Some GPS receivers allow DOP settings to be manipulated by the user.



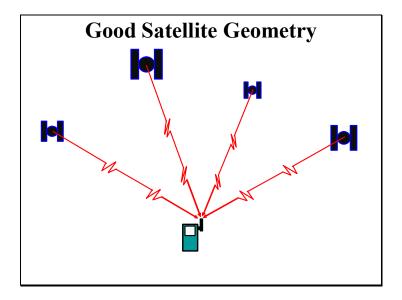
Ideal Satellite Geometry (Overhead View)

Satellite geometry refers to the positions of satellites relative to each other in space. Dilution of Precision (DOP) is an indicator of the quality of a GPS receiver's triangulated position relative to the quality of the geometric positions of the satellites whose signals the receiver is using. GPS receivers get satellite position information from the ephemeris message sent as part of the data stream from each satellite. There are different types of DOP, such as vertical dilution of precision (VDOP), horizontal position of dilution (HDOP), geometric dilution of precision (GDOP), and position dilution of precision (PDOP). Dilution of precision uses numerical values to represent the quality of satellite geometry, from 1 to over 100. The lower the PDOP value the better the accuracy of position fixes. Some high-end GPS receivers (such as Trimble data loggers) have a default PDOP setting of around 8, and the value can be changed to meet the needs of the user. Garmin receivers do not allow PDOP manipulation by the user, nor do they provide a PDOP value. Instead they use a position of error (EPE) value in feet or meters which provides an estimate of the amount of horizontal error caused by poor satellite geometry.

**Position Dilution of Precision (PDOP)** is of most concern to GPS users. PDOP is specifically the calculated likelihood of position error based on the present position of the satellites being tracked, including horizontal and vertical errors. The satellite configuration in this diagram represents the best possible geometry for low PDOP, assuming only four satellites are being acquired by the GPS receiver. The outer ring of the blue circle (the sky) represents the earth's horizon. The center of the cross hair represents the sky directly above the receiver. This satellite configuration will generally provide the best

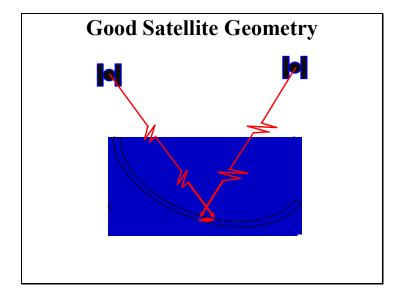
3D positioning because any horizontal error from one direction will be offset by the opposing satellites. The satellite directly overhead improves vertical accuracy.

Slide 34



## **Good Satellite Geometry (Profile View)**

The best satellite configuration for optimum receiver positioning is one satellite directly above the receiver, and three or more satellites equally spaced around the horizon. In this configuration satellite geometry is very good since distance measurements are from all directions. The area where all four pseudo-ranges intersect will be much smaller, providing a more precise position.

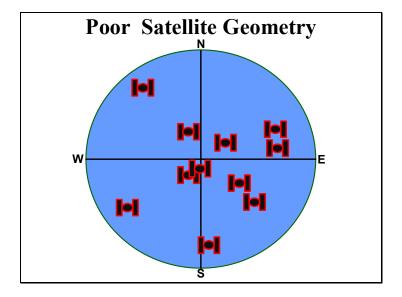


#### Good Satellite Geometry (cont.)

Satellite range errors contribute to dilution of precision (DOP). Range errors prevent perfect intersection of the satellite ranges. The farther apart the satellites are from each other (better geometry resulting in low PDOP) the smaller the red diamond will be in this diagram. Low PDOP results in a much smaller area of position uncertainty (the red diamond).

Global Positioning System receivers will attempt to weed out satellite signals that prevent good position trilateration. A receiver will choose four satellites spread out across the sky rather than four satellites bunched close together in one quadrant of the sky. But it should be noted that a receiver's priority is always to provide a position, even a poor position, regardless of satellite geometry. The reasoning is that any GPS position information provided by the receiver is better than no position information. This also explains why GPS receivers will provide a 2D (two-dimensional) position even though it may be off by a considerable distance on the ground.

Most GPS receivers provide some means of determining satellite geometry, either graphically (as in Garmin receivers), or through satellite position information (as in Trimble receivers). Garmin receivers use a sky view display to show the locations of GPS satellites above the receiver. A user can visually check satellite geometry, as well as the strength of the satellite signals, using Garmin's initial startup screen. Other brands of receivers may use a similar or different method of displaying satellite geometry and signal strength. When using Trimble brand receivers, the best way to verify good satellite geometry is through the displayed PDOP value.



#### **Poor Satellite Geometry**

(Note: To properly view the animation in this diagram, use Slide Show feature of PowerPoint.)

The locations of satellites in relation to each other in space at any given time can affect the quality of a GPS receiver's position fix. Spaced low on the horizon, with no satellite directly above the receiver, can result in a high PDOP. Similarly, if all satellites acquired by a receiver are bunched closely together in one quadrant of the sky can also result in poor triangulation measurements (and a high DDOP). Topography on the ground also affects satellite geometry. A receiver inside a vehicle, near tall buildings, under dense canopy, or in mountainous areas can be affected by blocked signals. GPS requires line of sight between receiver and satellite.

Each PowerPoint animation in this diagram corresponds to the following sets:

**Satellite set 1:**This satellite configuration results in poor PDOP and HDOP, but good VDOP. This is an example of a poor satellite configuration for achieving a precise position.

**Satellite set 2:** This satellite configuration represents poor PDOP and VDOP, but good HDOP. It's important to remember that satellite geometry that is poor for one kind of DOP can actually be good for another DOP. If you need the best horizontal measurements, but don't care about vertical accuracy, then this example is an acceptable satellite configuration.

**Satellite set 3:**This satellite configuration represents poor PDOP, VDOP, and HDOP. This is another example of a poor satellite configuration.

GDOP: Geometric Dilution of Precision (refers to GPS satellite orbit anomalies)

VDOP: Vertical Dilution of Precision (imperfect height measurements on the ground)

HDOP: Horizontal Dilution of Precision (imperfect horizontal measurements on the ground)

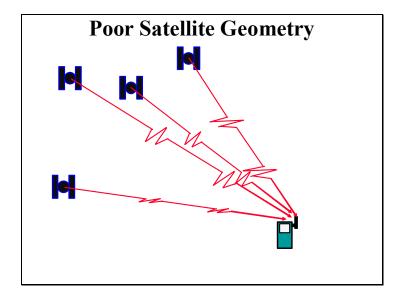
TDOP: Time Dilution of Precision (refers to slight anomalies in time measurements)

PDOP: Position Dilution of Precision (three-dimensional position errors)

\_\_\_\_\_

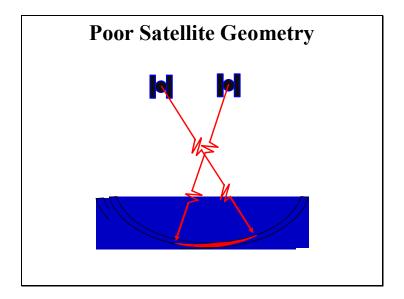
\_\_\_\_\_\_

Slide 37



**Satellite Geometry (cont)** 

In this diagram the receiver's position accuracy will not be very good. All of the acquired satellite signals are bunched close together in one or two quadrants of the sky. The area of probable error will be relatively high (see next diagram).

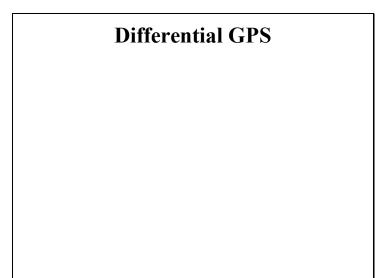


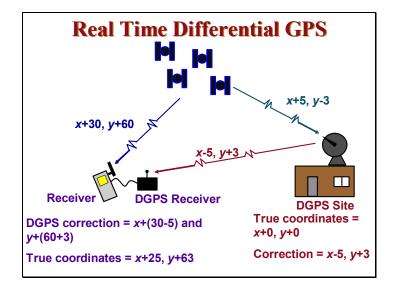
## Satellite Geometry (cont)

Most of the time there are more satellites available than a receiver needs to triangulate a position fix, so the receiver can pick satellites which will provide reasonably good geometry for the receiver to triangulate a precise position. However, if the receiver happens to acquire satellites that are bunched close together in the sky, the intersecting circles that define a position will cross at very shallow angles. This increases the potential area of error around a position. In this diagram, two satellites close together will emit radio signals which cross at a shallow angle, producing a large area of potential error on the ground (the red diamond). Add several more satellites with the same tight pattern, and the resulting PDOP will be very high.

\_\_\_\_

Slide 39





#### **Real Time Differential GPS**

\*This is an example of <u>real time</u> DGPS. This is not a representation of post data collection correction done in the office on a computer using software such as Trimble's Pathfinder.

Real-time DGPS employs a second, stationary GPS receiver at a precisely measured spot (usually established through traditional survey methods). This receiver corrects any errors found in the GPS signals, including atmospheric distortion, orbital anomalies, Selective Availability (when it existed), and other errors. A DGPS station is able to do this because its computer already knows its precise location, and can easily determine the amount of error provided by the GPS signals. DGPS corrects or reduces the effects of:

Orbital errors

Atmospheric distortion

Selective Availability

Satellite clock errors

Receiver clock errors

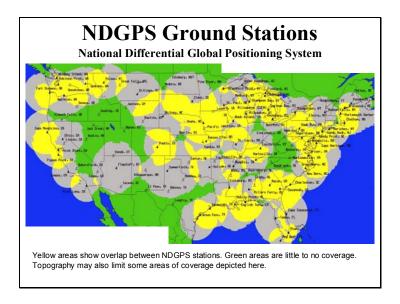
DGPS cannot correct for GPS receiver noise in the user's receiver, multipath interference, and user mistakes. In order for DGPS to work properly, both the user's receiver and the DGPS station receiver must be accessing the same satellite signals at the same time. This requires that the user's receiver not be more than 300 miles from the DGPS station (100 miles or less is considered optimum).

In the diagram example, the DGPS station receives GPS signals telling the station that its location is x+5, y-3. But the station already knows that its true location is x+0, y+0. So it calculates a correction of x-5, y+3, and transmits this correction out to the field. The DGPS receiver in the field uses this correction factor to update the same GPS radio signals it's receiving. Here the GPS receiver triangulates its position using the GPS as x+30, y+60. The DGPS

receiver provides the correction factor to the GPS receiver's processor, which calculates its correct position at x+25, y+63. The user can generally get accurate position fixes within a few meters or less using DGPS.

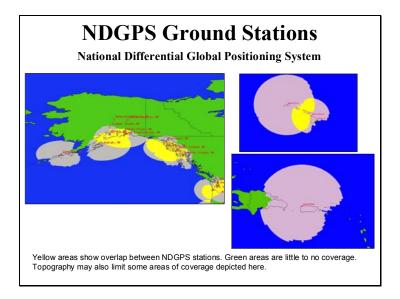
Many high-end GPS receivers are built with DGPS capability, while some low-end receivers can be configured for DGPS using add on hardware. There are a number of free and subscription services available to provide DGPS corrections. The U.S. and Canadian Coast Guards and U.S. Army Corps of Engineers transmit DGPS corrections through marine beacon stations.

The Wide Area Augmentation System (WAAS) was developed by the FAA as another kind of highly advanced DGPS. This technology is currently being adopted by many GPS receiver manufacturers (including Garmin) to create more accurate receivers. (More on WAAS at the end of this lesson.)



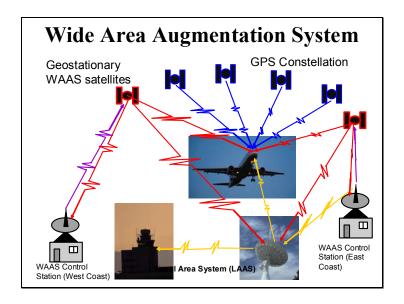
#### **NDGPS Ground Stations**

The map shows areas of likely DGPS coverage by ground stations in the U.S. New NDGPS stations are coming online on a regular basis, so this map may be outdated. The map shows areas of little or no differential GPS coverage in the United States, with the Rock Mountains being most devoid of NDGPS coverage. Notice that virtually all coastlines in the U.S. are covered by NDGPS (see next slide for Alaska, Hawaii and the Caribbean).



**NDGPS Ground Stations (cont.)** 

\_\_\_\_\_



#### **Wide Area Augmentation System**

The precision and accuracy of the Global Positioning System limits its use for aircraft landings and in-flight navigation. As described earlier, satellite position errors, clock drift, and the Earth's atmosphere all enhance GPS position errors (both vertically and horizontally). However, the Federal Aviation Administration (FAA) realized the value in enhancing the GPS to provide for better aircraft navigation. Currently under development (the system has not yet been approved for aviation), the Wide Area Augmentation System (WAAS) is designed to enhance and improve satellite navigation over the continental United States, and portions of Mexico and Canada. Unlike the GPS, which is funded and maintained by the U.S. military, the WAAS is funded by the FAA and Department of Transportation. It is specifically meant for civilian and commercial applications within the United States.

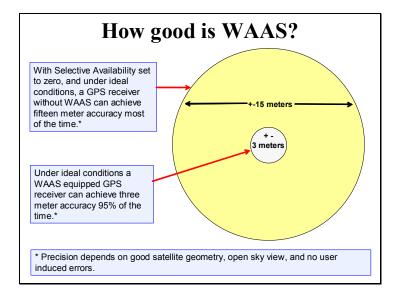
Think of WAAS as a highly advanced real-time differential GPS. But instead of using ground based transmitters to broadcast position correction information, WAAS uses its own geostationary satellites in fixed orbit over the United States. There are 25 ground reference stations positioned across the United States (including three in southern Alaska, and one each in Puerto Rico and Hawaii) that monitor GPS satellite data. These stations continuously receive GPS signals and correct that satellite information against their own known precise positions. Each ground station (referred to as a Wide Area Reference Station, or WRS) then sends its corrected GPS data to one of two master control stations located on the Pacific and Atlantic coasts. The master control stations create a correction message that weeds out atmospheric distortion, GPS satellite orbit and clock errors, time errors and other errors. This message is then broadcast to the two WAAS satellites. These in turn re-broadcast the correction information using the basic GPS signal structure: L1 ("Link One") on frequency 1575.42MHz. This allows any WAAS capable GPS receiver to pick up the corrected WAAS signal.

In addition to the space based satellite based WAAS, the FAA is installing ground based Local Area Augmentation Systems (LAAS) at most major airports in the U.S. Working in conjunction with the space segment of WAAS, the LAAS will allow for even greater accuracy for aircraft during takeoffs and landings. The LAAS uses reference

receivers located near airport runways, giving much more accurate correction data to incoming aircraft. However, currently the WAAS has not been approved for aviation by the FAA due to refinements still needed in the system to improve vertical and horizontal accuracy during Category 1 takeoffs and landings (i.e. very close to the runway under low visibility conditions).

Unlike differential GPS which requires additional equipment to work, the WAAS is available to anyone in the United States, much of Canada, and portions of northern Mexico, equipped with a WAAS capable GPS receiver. Since the WAAS uses the same signal transmission scheme as the GPS, it's immediately available to all GPS users. While not yet ready for general aviation navigation, WAAS is already enhancing marine navigation around coastlines and harbors, terrestrial mapping and navigation, and commercial tracking and navigation. WAAS capable GPS receivers are now available for as little as \$120 (such as the Garmin e-Trex).

The diagram shows the complexity of the Wide Area Augmentation System as it fits into the existing radio and navigation system used by aviation. The GPS satellites (in blue) continuously transmit information which is picked up by 25 WAAS ground stations scattered around the U.S. These stations send an updated data stream to the two Master Control Stations (gray) located on the East and West coasts. These stations transmit a correction message (purple) back to the WAAS geostationary (GEOS) satellites (red), which re-transmit the updated data using the GPS signal structure (red). Any WAAS enabled GPS receiver can pick up this signal. Updated data is also sent to local area augmentation system (LAAS) sites located at or near airports, which is eventually transmitted directly to aircraft (yellow) for precise landings and takeoffs in low visibility conditions.



**How Good is WAAS?** 

The Wide Area Augmentation System (WAAS) dramatically improves existing GPS technology for positional accuracy (in the United States and portions of Canada and Mexico). Under ideal conditions, with Selective Availability set to zero, horizontal accuracy with GPS can be fifteen meters or less. Under the same conditions with WAAS that horizontal accuracy can be reduced as low as three meters or less. Bear in mind that many factors dictate the level of accuracy that can be achieved by any GPS receiver on the ground. Among these factors include errors in the GPS, multipath interference, atmospheric errors, closed canopy or other signal blockers, and human error. Combined these errors can degrade positional accuracy to 100 meters or more. For WAAS, two downsides are its reduced capability under heavy canopy (trees, canyons, etc.), and its limitation to mostly the contiguous U.S. (and portions of northern Mexico, southern Canada, Hawaii, the Caribbean, and Alaska).